# LCLS-II – Project and Engineering Challenges

## MEDSI 2014, Melbourne

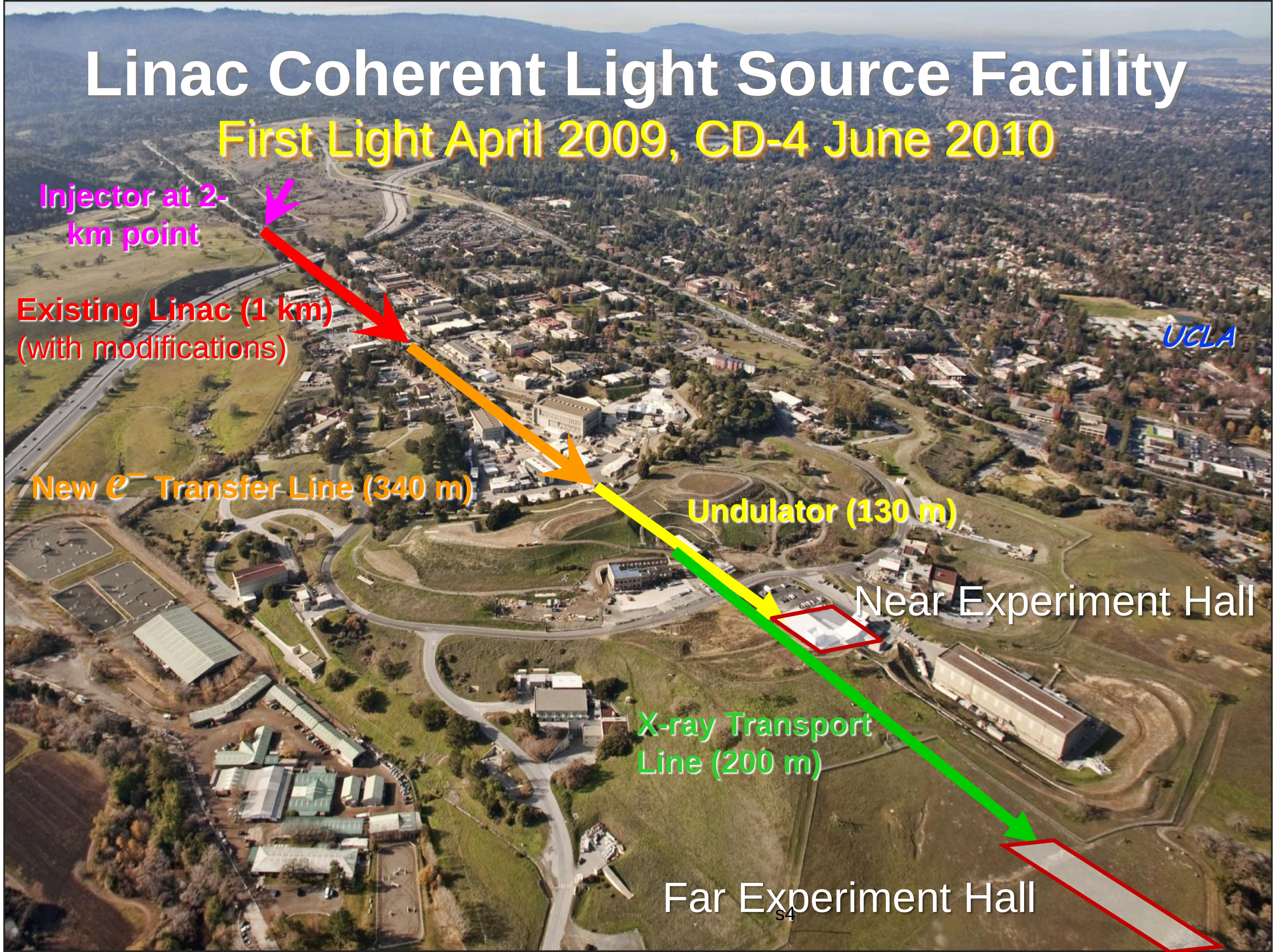
Nicholas M. Kelez 10/21/2014

# Outline

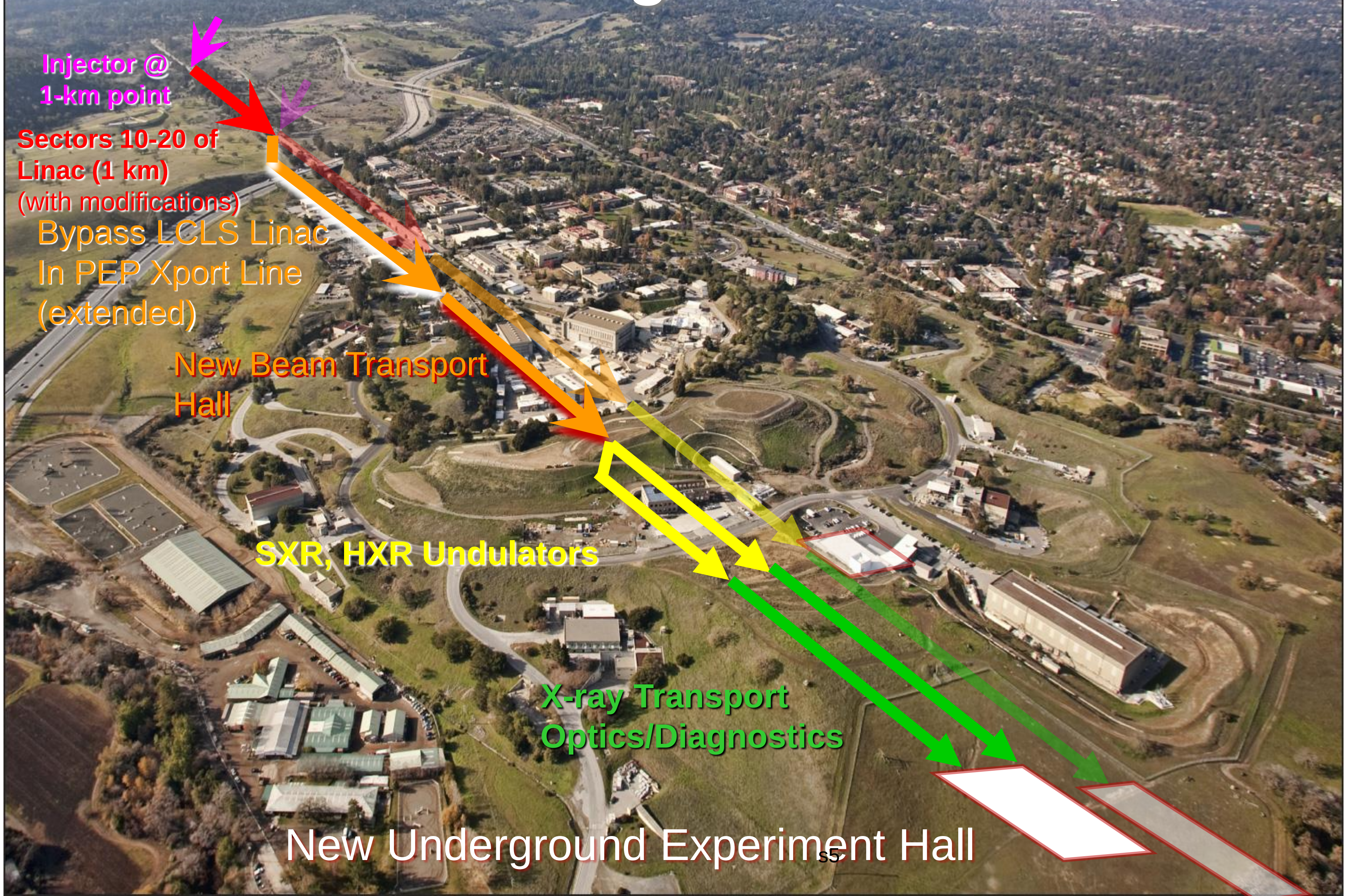
- LCLS-II Project Overview
- Accelerator Components and Engineering Challenges
- Future Outlook

# LCLS Timeline


1992: Proposal (Pellegrini), Study Group(Winick)
1994: National Academies Report
1996: Design Study Group (M. Cornacchia)
1997: BESAC (Birgeneau) Report
1998: LCLS Design Study Report
1999: BESAC (Leone) Report
2000: LCLS-First Experiments (Shenoy & Stohr)
2001: DOE Critical Decision 0
2002: LCLS Conceptual Design Report and DOE Critical Decision 1
2003: DOE Critical Decision 2A
2004: DOE 20-Year Facilities Roadmap
2005: DOE Critical Decision 2B and 3A
2006: DOE Critical Decision 3B
2009: First Light, 10 April 2009
2009: First Light to First Instrument August 19 2009
2009: First Instrument Commissioned September 12, 2009
2009: LCLS-II Critical Decision 0
2010: LCLS CD-4 June 2010
2011: LCLS-II Critical Decision 1 Review April 26, 2011
2011: LCLS-II Critical Decision 3a Review Dec 6, 2011
2012: Final Instrument Commissioned April 4, 2012
2012: LCLS-II Critical Decision 2 Review Aug 21, 2012
2013: BESAC Subcommittee Report July 25, 2013
2014: LCLS-II Critical Decision 1 Review Feb 4, 2014
2014: LCLS-II CD1 Aug 22, 2014
2015: LCLS-II Critical Decision 2 Review Feb 2015 ?



Linac Coherent Light Source Facility
First Light April 2009, CD-4 June 2010
Injector at 2-km point
Existing Linac (1 km)
(with modifications)
UCLA
New $e^-$ Transfer Line (340 m)
Undulator (130 m)
Near Experiment Hall
X-ray Transport Line (200 m)
Far Experiment Hall

# Linac Coherent Light Source II – phase1



# BESAC Subcommittee Report: July 25, 2013

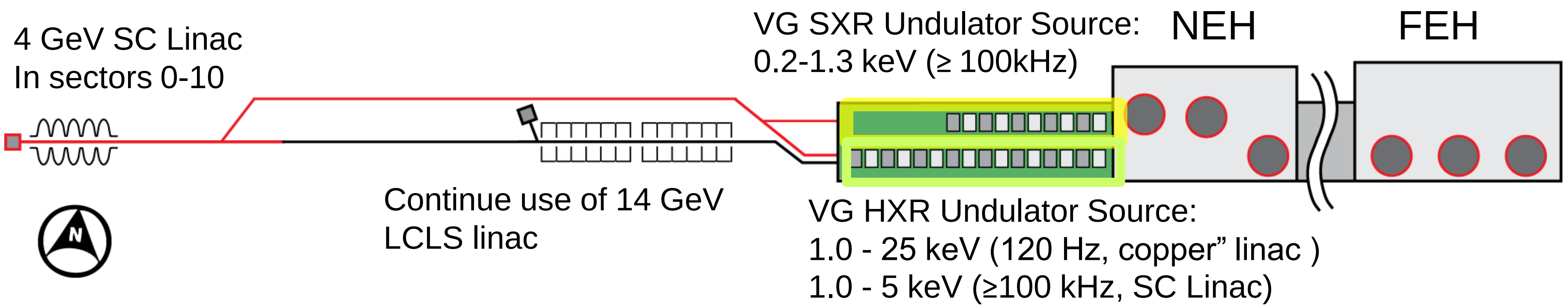
- Committee report & presentation to BESAC:
  - "It is considered essential that the new light source have the pulse characteristics and **high repetition rate** necessary to carry out a broad range of coherent "pump probe" experiments, in addition to a sufficiently broad photon energy range (**at least *~0.2 keV to ~5.0 keV***)"
  - "It appears that such a new light source that would meet the challenges of the future by *delivering a capability that is beyond that of any existing or planned facility worldwide is now within reach.* **However, *no proposal presented to the BESAC light source sub-committee meets these criteria*."**
  - "The panel recommends that a decision to proceed toward a new light source with revolutionary capabilities be accompanied by a robust R&D effort in accelerator and detector technology that will maximize the cost-efficiency of the facility and fully utilize its unprecedented source characteristics."

# Project Collaboration

| | |
|---|---|
| Fermilab | • 50% of cryomodules: 1.3 GHz<br>• Cryomodules: 3.9 GHz<br>• Cryomodule engineering/design<br>• Helium distribution<br>• Processing for high Q (FNAL-invented gas doping) |
| Jefferson Lab — EXPLORING THE NATURE OF MATTER | • 50% of cryomodules: 1.3 GHz<br>• Cryoplant selection/design<br>• Processing for high Q |
| BERKELEY LAB | • Undulators<br>• $e^-$ gun & associated injector systems |
| Argonne NATIONAL LABORATORY | • Undulator Vacuum Chamber<br>• Also supports FNAL w/ SCRF cleaning facility<br>• Undulator R&D: vertical polarization |
| CORNELL UNIVERSITY FOUNDED A.D. 1865 | • R&D planning, prototype support<br>• processing for high-Q (high Q gas doping)<br>• $e^-$ gun option |

# A New LCLS-II Project  Redesigned in Response to BESAC

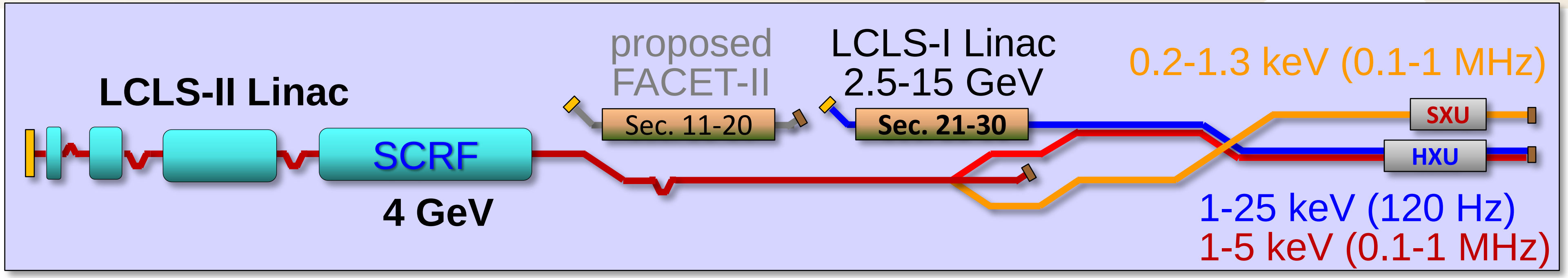
| | |
|---|---|
| **Accelerator** | <u>**Superconducting linac**</u>: 4 GeV |
| **Undulators in existing LCLS-I Tunnel** | New variable gap (north)<br>New variable gap (south), replaces existing fixed-gap und. |
| **Instruments** | Re-purpose existing instruments (instrument and detector upgrades needed to fully exploit) |
| **Total Project Cost** | $965M |



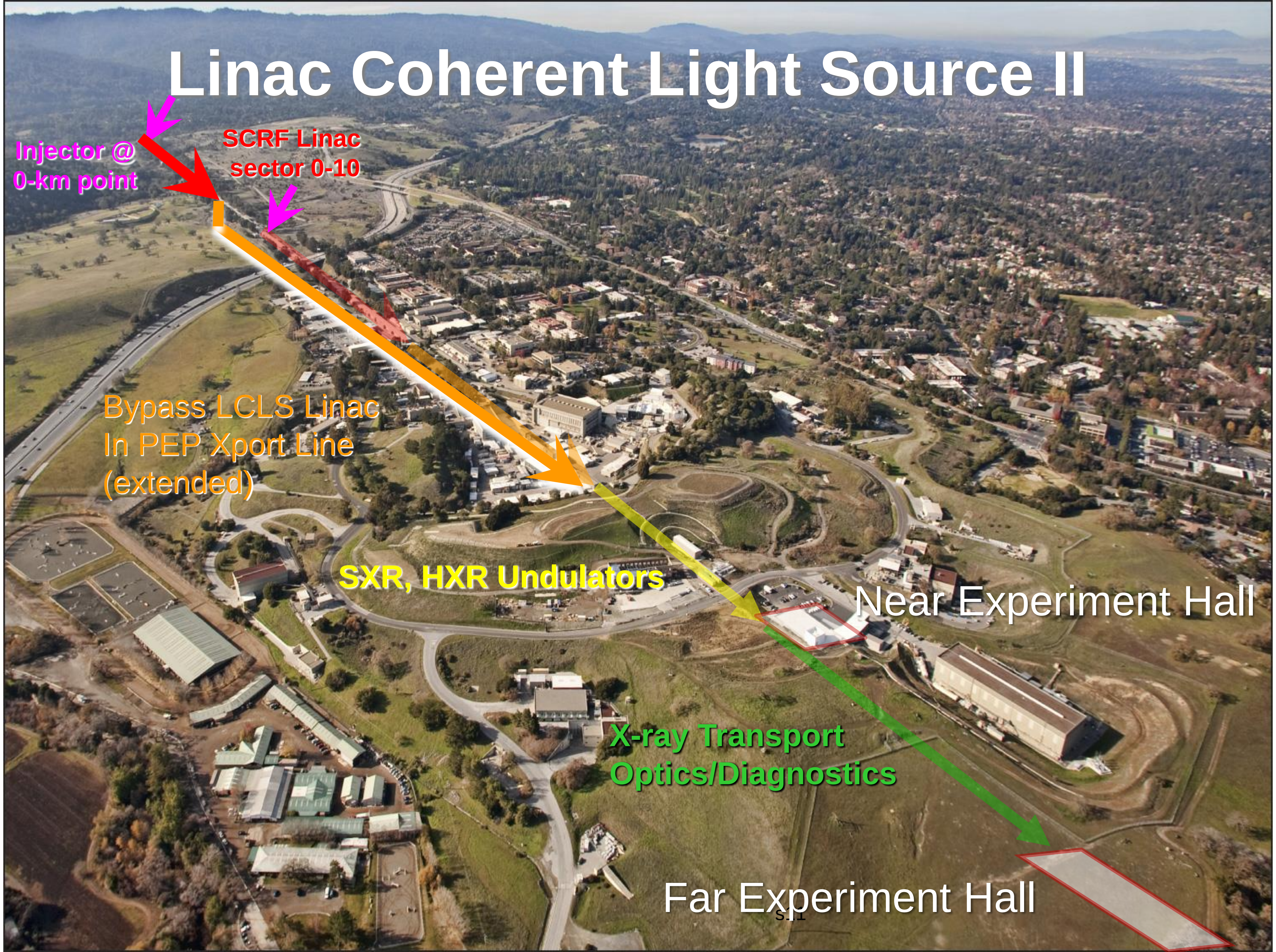
# LCLS-II Accelerator Design - Plan for rapid construction

- New linac based on 1.3 GHz SCRF with MHz beam rate
  - 1.3 GHz technology well established around the world
  - Similar to LCLS with laser heater, harmonic linearizer and dual bunch compressor (and option for third compressor at linac end)
  - Link into existing LCLS beamlines
- Dual variable gap hybrid undulators to cover energy range
  - Self-seeding in both HXR and SXR undulators with options for additional photon phase space control
- Leverage partner labs and extensive work on NGLS, NLS, EU-XFEL, ILC and LCLS-II$_{\text{Phase I}}$ to develop conceptual design
  - Project definition occurred very rapidly (fall of 2013)

# LCLS-II Accelerator Layout and Modifications




- New Injector, SCRF linac, and extension installed in Sectors 0-10
- Use existing Bypass line from Sector 10 → Beam Switch Yard (BSY)
- Re-use existing high power dump in BSY and add magnetic kicker to direct beams to dump, SXR, or HXR
- Re-use existing transfer line (LTU) to HXR; modify HXR dump
- Construct new LTU to SXR and new dump line


Linac Coherent Light Source II
Injector @
0-km point
SCRF Linac
sector 0-10
Bypass LCLS Linac
In PEP Xport Line
(extended)
SXR, HXR Undulators
Near Experiment Hall
X-ray Transport
Optics/Diagnostics
Far Experiment Hall

# LCLS-II (SCRF) Baseline Parameters

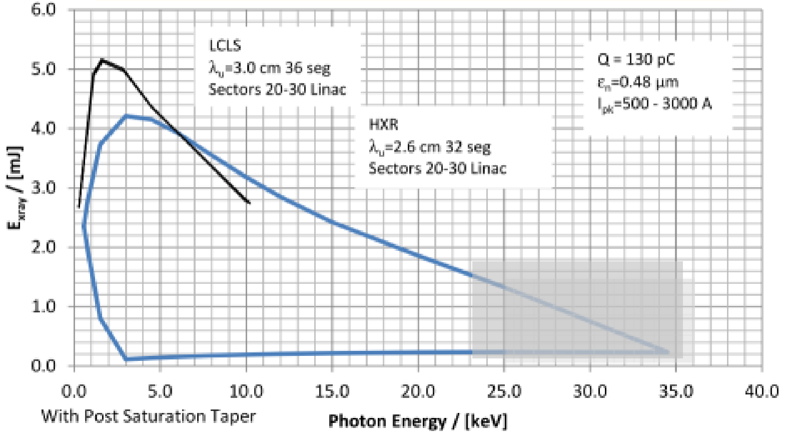
| Parameter | symbol | nominal | range | units |
|---|---|---|---|---|
| Electron Energy | $E_f$ | **4.0** | 2.0 - 4.14 | GeV |
| Bunch Charge | $Q_b$ | **100** | 10 - 300 | pC |
| Bunch Repetition Rate in Linac | $f_b$ | **0.62** | 0 - 0.93 | MHz |
| Average $e^-$ current in linac | $I_{avg}$ | **0.062** | 0.0 - 0.3 | mA |
| Avg. $e^-$ beam power at linac end | $P_{av}$ | **0.25** | 0 - 1.2 | MW |
| Norm. rms slice emittance at undulator | $\gamma\varepsilon_{\perp\text{-}s}$ | **0.45** | 0.2 - 0.7 | μm |
| Final peak current (at undulator) | $I_{pk}$ | **1000** | 500 - 1500 | A |
| Final slice E-spread (rms, w/heater) | $\sigma_{Es}$ | **500** | 125 - 1500 | keV |
| RF frequency | $f_{RF}$ | **1.3** | - | GHz |
| Avg. CW RF gradient (powered cavities) | $E_{acc}$ | **16** | - | MV/m |
| Avg. Cavity Q0 | $Q0$ | **2.7e10** | 1.5 - 5e10 | - |
| Photon energy range of SXR (**SCRF**) | $E_{phot}$ | - | **0.2 - 1.3** | keV |
| Photon energy range of HXR (**SCRF**) | $E_{phot}$ | - | **1 - 5** | keV |
| Photon energy range of HXR (**Cu-RF**) | $E_{phot}$ | - | **1 - 25** | keV |

# LCLS-II SASE Performance:

## Photons/Pulse

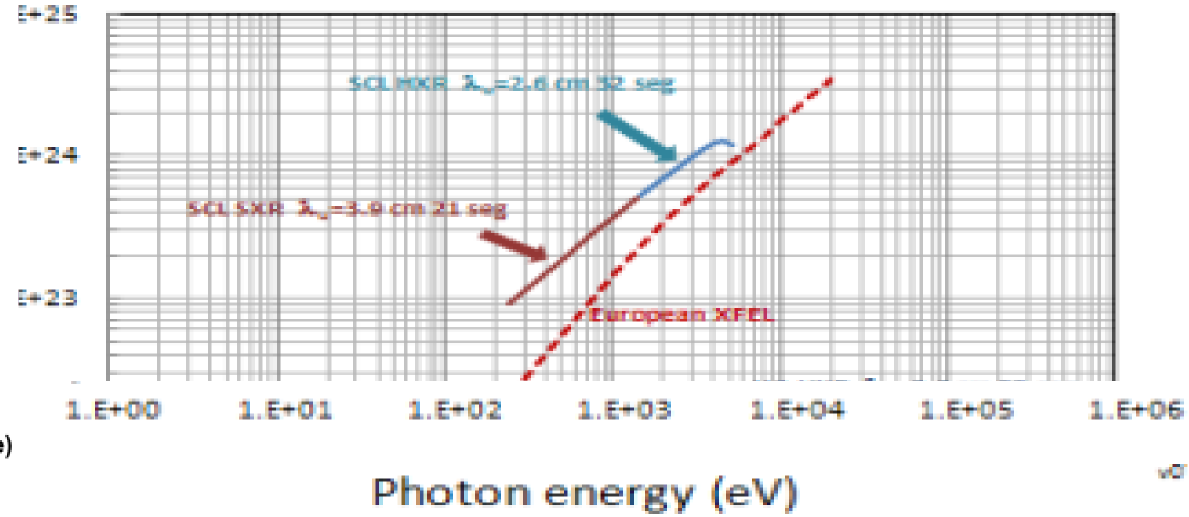
## Average Brightness

### Cu-Linac Photon Energy Range



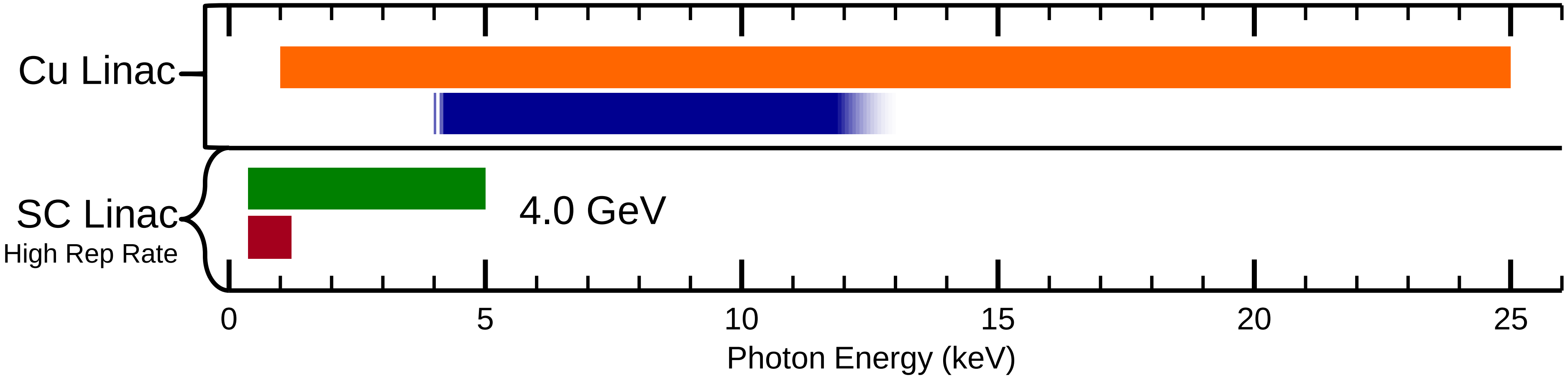

**Calculated X-ray pulse energies versus photon energy for the CuRF linac (blue) and the similar curve for the existing LCLS (black).**

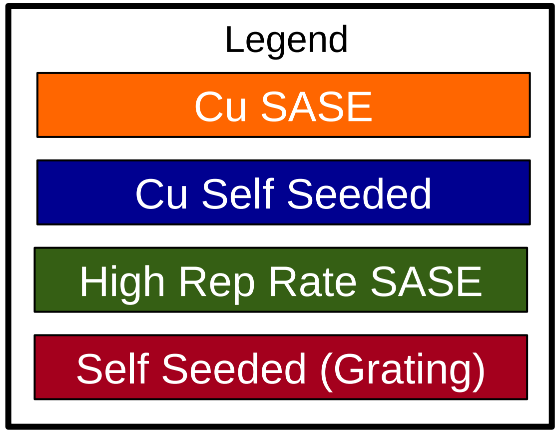
### SC Linac: Photon Energy Range (eV)




| Performance Measure | Threshold | Objective |
|---|---|---|
| Variable Gap Undulators | 2 (SXR & HXR) | 2 (SXR & HXR) |
| **Super Conducting Linac Based FEL System** | | |
| Super Conducting Linac Electron Beam Energy | 3 GeV | ≥ 4 GeV |
| Super Conducting Linac Repetition Rate | 50 kHz | 1,000 kHz |
| Super Conducting Linac Charge per Bunch | 0.02 nC | 0.1 nC |
| Photon Beam Energy Range | 0.25-2 keV | 0.2-5 keV |
| High Repetition Rate Capable End Stations | ≥ 1 | ≥ 3 |
| FEL per-pulse intensity on-axis | 10X spontaneous | >10^11 photons in 10^-3 BW |
| **Normal Conducting Linac Based FEL System** | | |
| Normal Conducting Linac Electron Beam Energy | 13 GeV | 15 GeV |
| Normal Conducting Linac Repetition Rate | 120 Hz | 120 Hz |
| Normal Conducting Linac Charge per Bunch | 0.1 nC | 0.25 nC |
| Photon Beam Energy Range | 1-8 keV | 1-25 keV |
| Low Repetition Rate Capable End Stations | ≥ 2 | ≥ 3 |
| FEL per-pulse intensity on-axis | 10X spontaneous @ 8 keV | >10^12 photons in 10^-3 BW @ 13 keV |

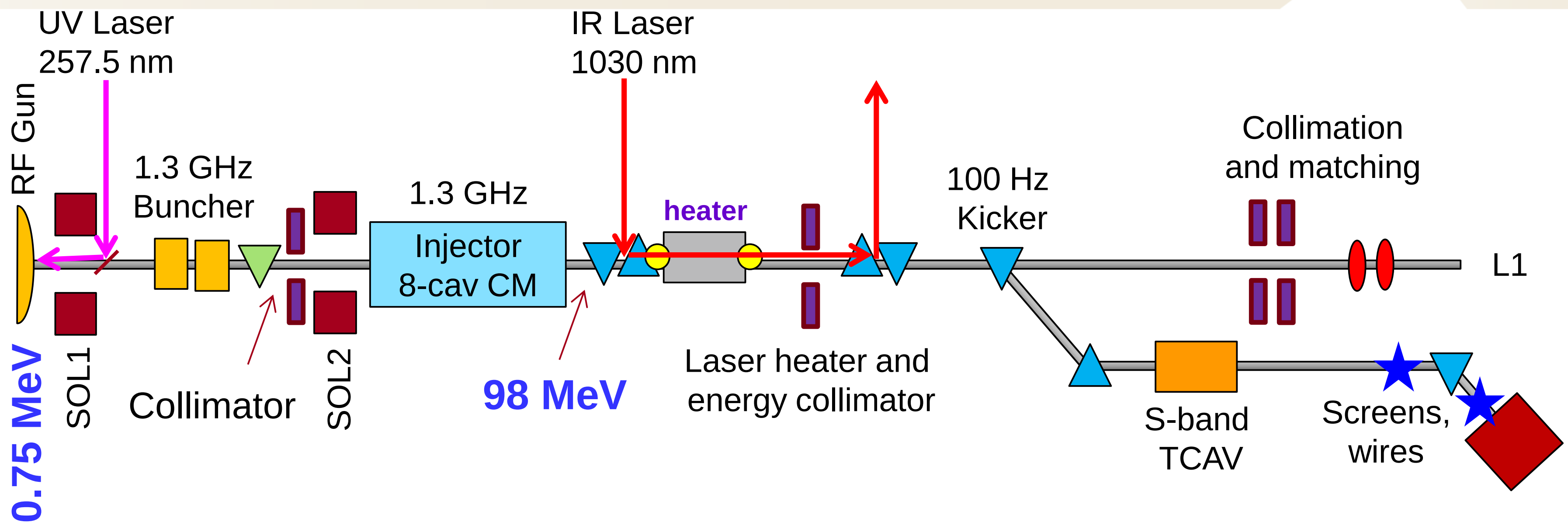
# SASE and Seeding - Building on LCLS Experience




- Hard X-Ray Source:
  - 1-5 keV w/ 4 GeV SC linac
  - Up to 25 keV with LCLS Cu Linac
- Soft X-Ray Source:
  - 250 eV-1.3 keV w/ 4 GeV linac
    - 200 eV requires <4 GeV

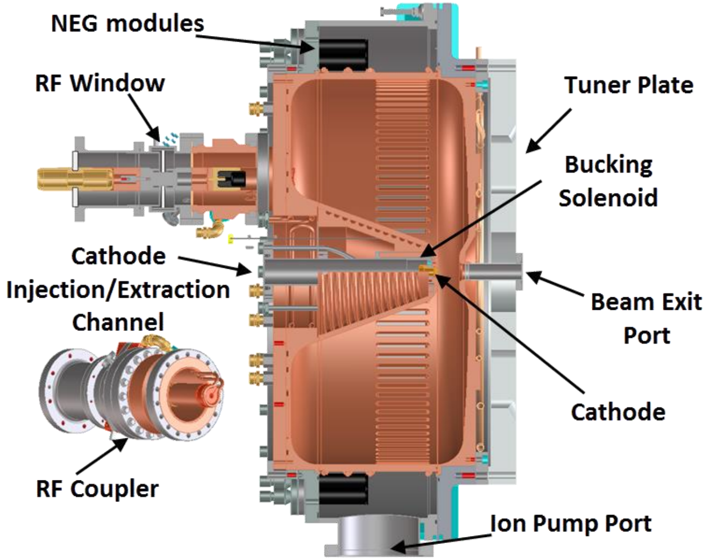
# Injector Baseline Layout




- CW (up to 1 MHz), 0.4 µm emittance @100pC
- Major injector components:
  - NC 185.7 MHz RF gun
  - $Cs_2Te$ cathode; UV/IR lasers for cathode/laser heater
  - NC 1.3 GHz buncher; two solenoids
  - SC 1.3 GHz 8-cavity CM (energy up to 100 MeV)

# The LBNL VHF RF Gun

**The Berkeley normal-conducting scheme satisfies and often overcomes all the X-FEL requirements.**



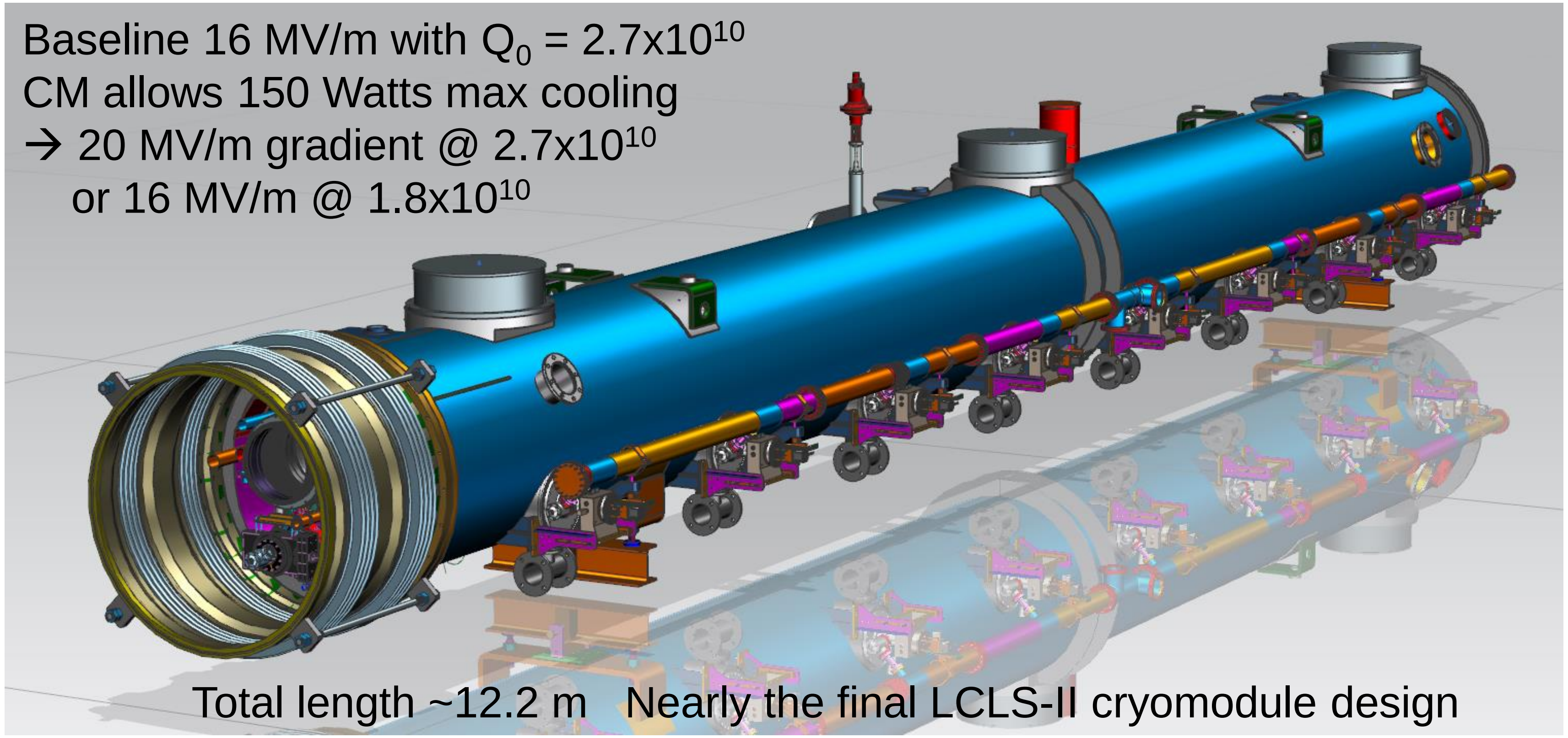

J. Staples, F. Sannibale, S. Virostek, CBP Tech Note 366, Oct. 2006

K. Baptiste, et al, NIM A 599, 9 (2009)

| | |
|---|---|
| Frequency ($7^{th}$ 1.3 GHz sub-Harmonic) | 186 MHz |
| Operation mode | CW |
| Gap voltage | 750 kV |
| Field at the cathode | 19.47 MV/m |
| $Q_0$ (measured) | 26500 |
| Shunt impedance | 6.5 MΩ |
| RF Power @ $Q_0$ | 100 kW |
| Peak surface field | 24.1 MV/m |
| Peak wall power density | 25.0 W/cm$^2$ |
| Accelerating gap | 4 cm |
| Diameter/Length | 69.4/35.0 cm |
| Operating pressure | ~ $10^{-10}$-$10^{-9}$ Torr |

- At the VHF frequency, the cavity structure is large enough to withstand the heat load and operate in CW mode at the required gradients.
- Also, the long $\lambda_{RF}$ allows for large apertures and thus for high vacuum conductivity.
- Based on mature and reliable normal-conducting RF and mechanical technologies.

# LCLS-II 1.3 GHz Cryomodule

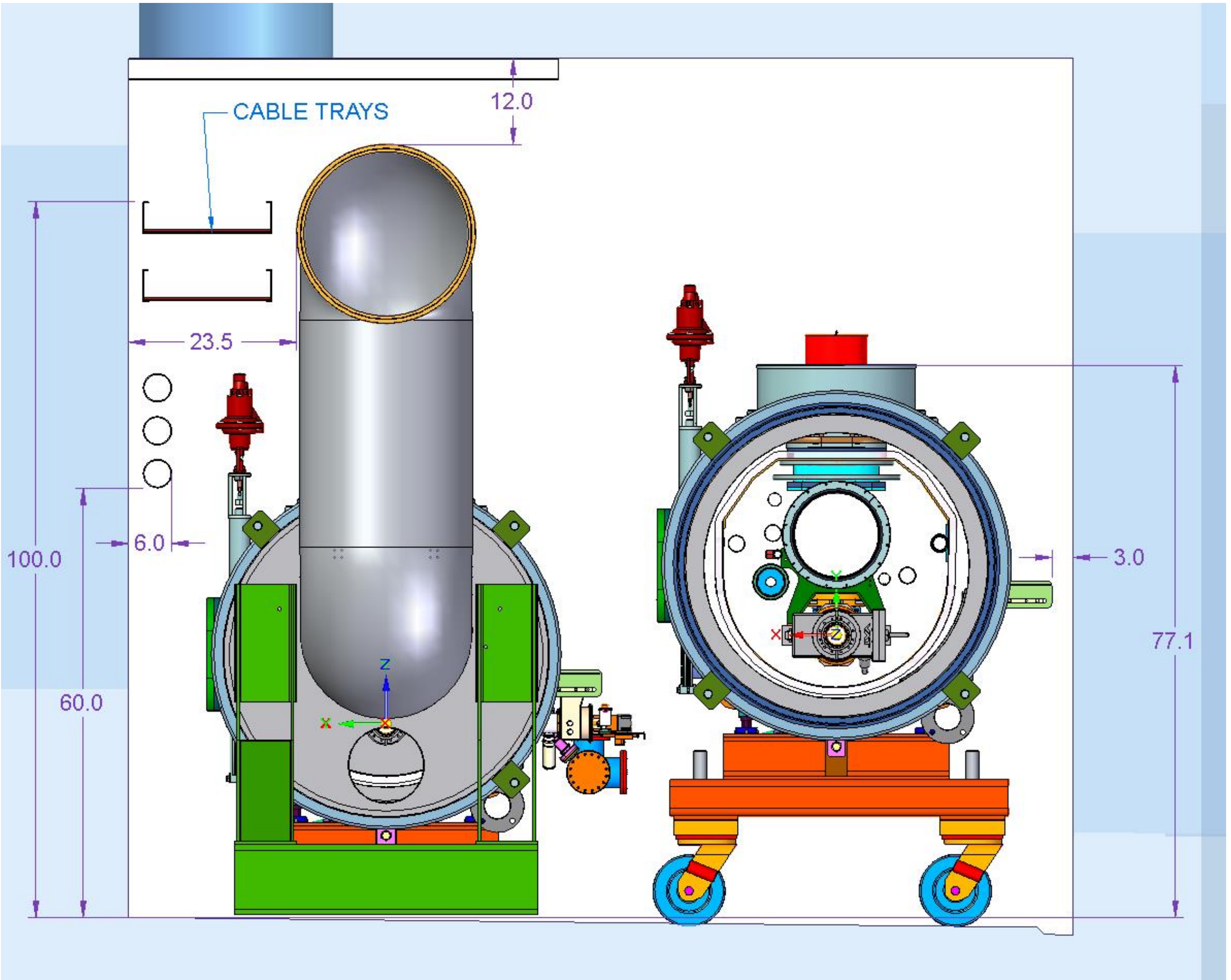



Cryomodules similar to EuXFEL with mods for CW operation
50% production led by FERMI
50% production led by J-LAB

# SCRF Linac in SLAC Tunnel

SLAC Linac Tunnel: 11 wide x 10 feet high - It will be a tight fit!

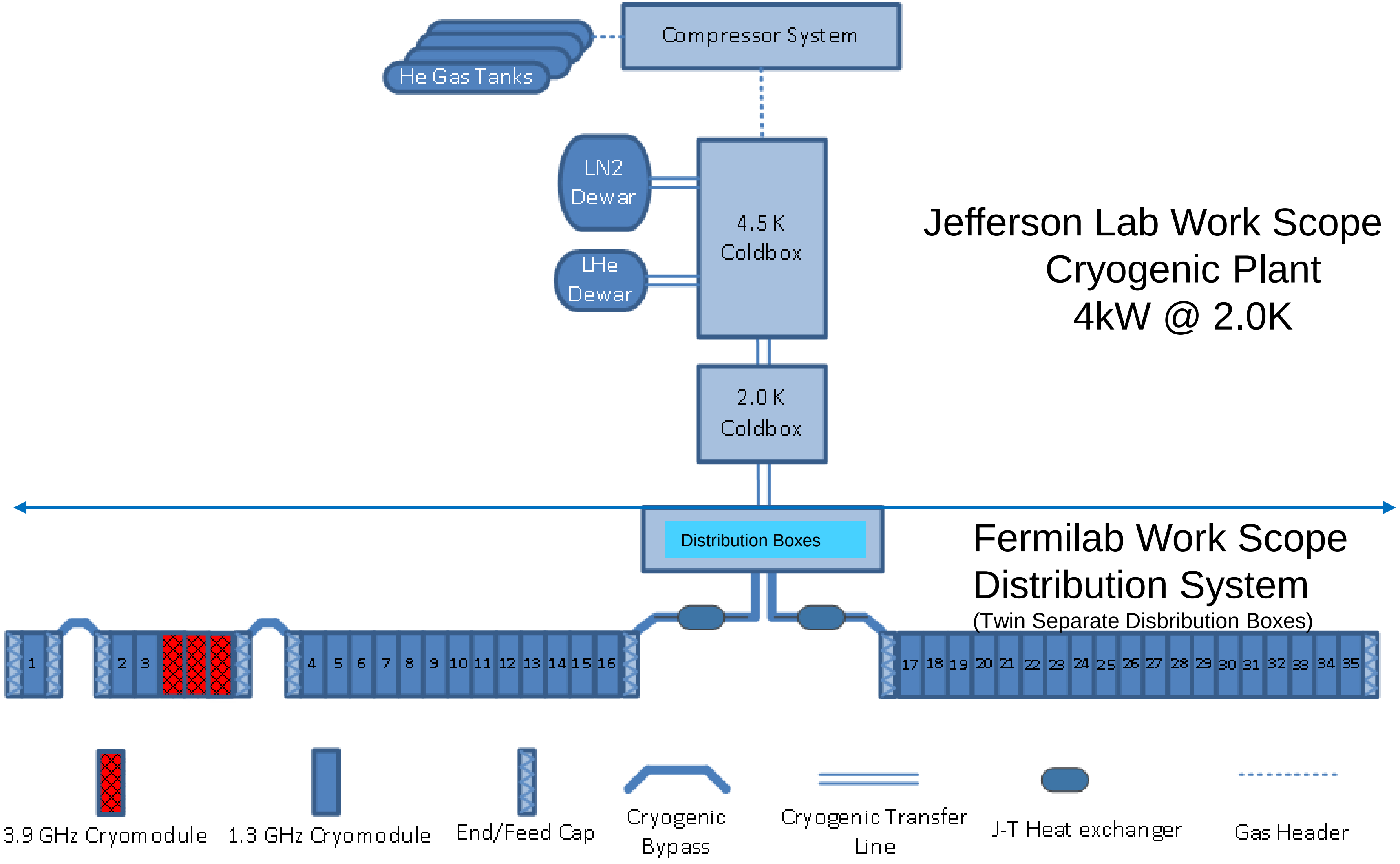
Plans for installation and servicing under development



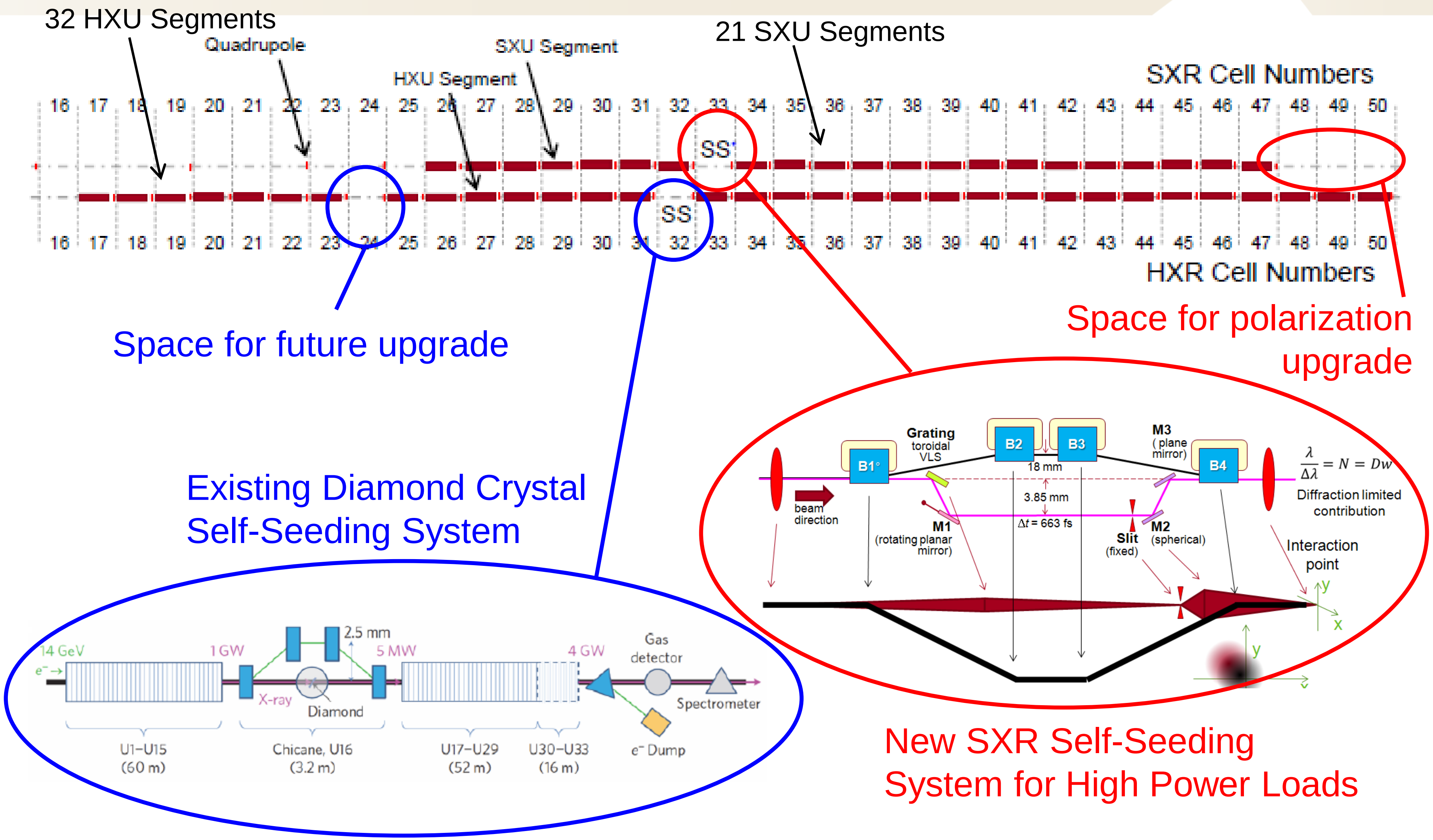



S. Boo, J. Chan

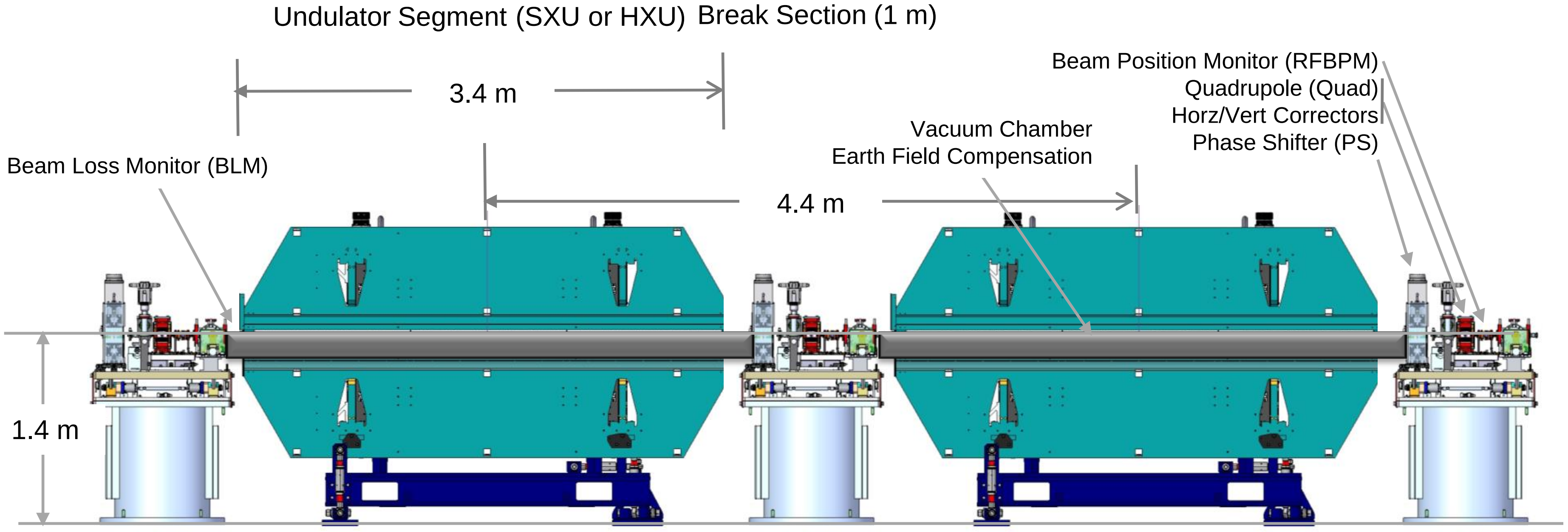
# Cryogenic Work Scope



# LCLS-II Undulator Layout and Self Seeding



# LCLS-II Segment and Break Section Layout.




**Layout shown for two individual undulator segments and three break sections for the HXR and SXR undulator lines.**

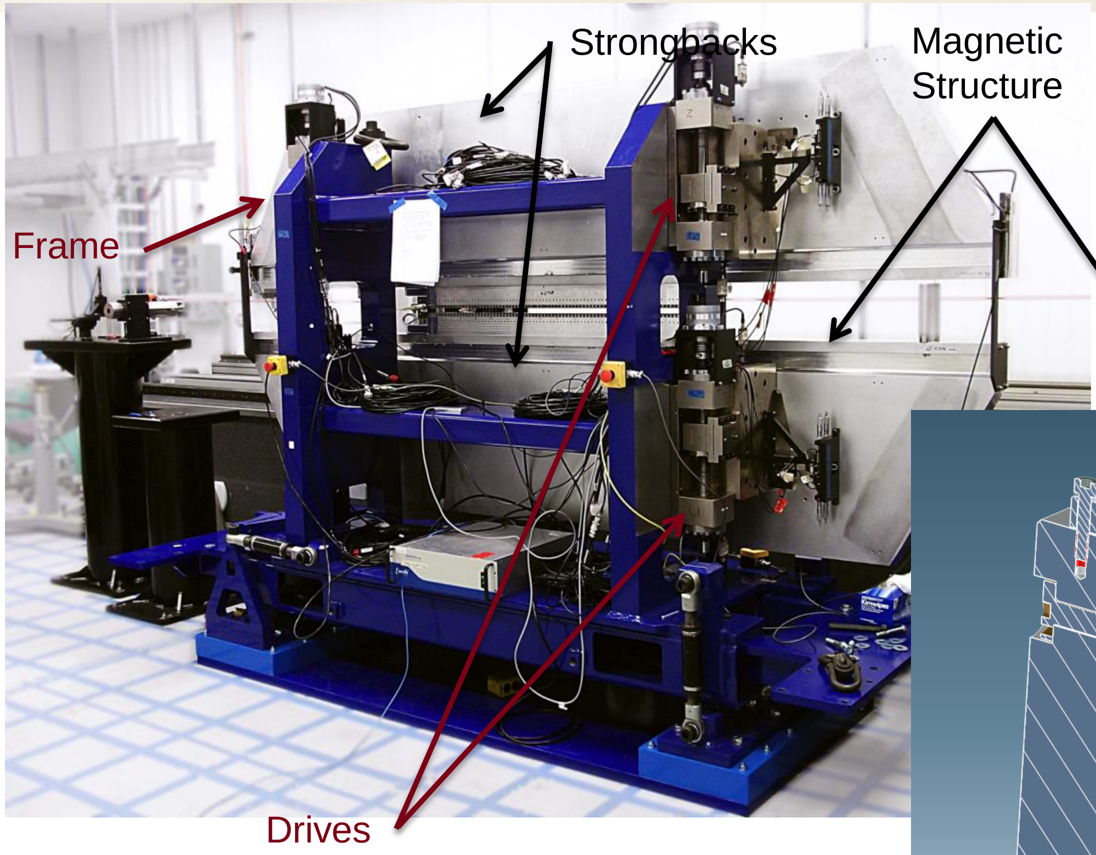
**Radiation damage to magnetic material is a serious concern**

- **e-beam collimation and halo control is critical**
- **Program for monthly monitoring planned**

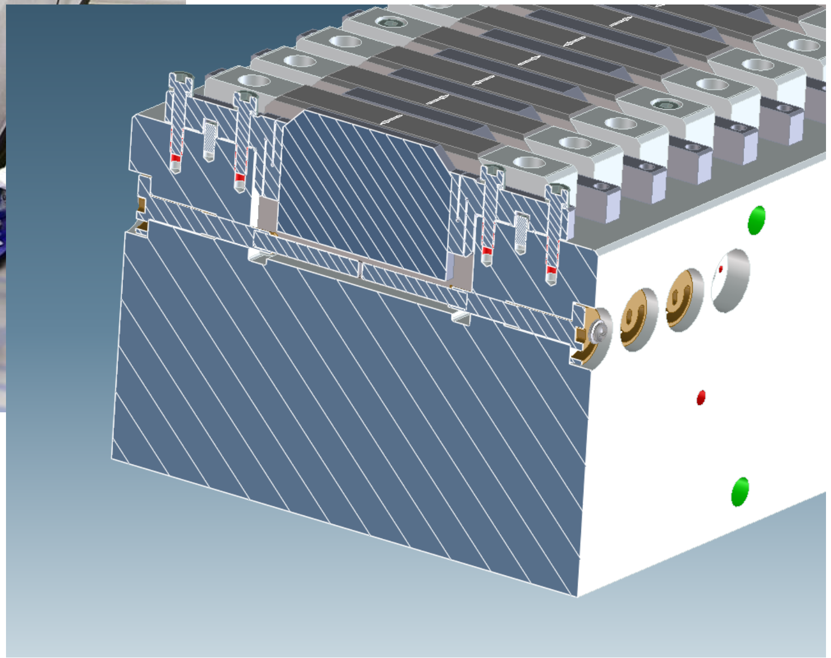
# Key Undulator Tolerances

| Parameter | HXU | SXU | Unit |
|---|---|---|---|
| $\Delta K_{eff}/K_{eff}$ | $\pm 2.3\times10^{-4}$ | $\pm 4.4\times10^{-4}$ | |
| $\Delta y_{align}$ | ±80 | ±150 | µm |
| $\Delta x_{align}$ | ±400 | ±400 | µm |
| First field integral range I1Bx, I1By | ±40 | ±40 | µTm |
| Second field integral range I2Bx, I2By | ±50 | ±50 | µTm$^2$ |
| Period error (rms) | <25 | <25 | µm |
| Maximum Phase Shake | ±5 | ±5 | degXray |
| Integrated sextupole field component | $<6.4\times10^{-4}$ | $<3.4\times10^{-4}$ | mm$^{-2}$ |
| Yaw error between strongbacks | ±1.0 | ±1.0 | mrad |
| Pitch error between strongbacks | ±0.035 | ±0.175 | mrad |
| Roll error between strongbacks | ±1.75 | ±1.75 | mrad |
| Environmental Field Error | ±0.1 | ±0.1 | G |

# Variable Gap Hybrid Undulators – Baseline




Full scale prototype nearly
Completed as part of LCLS-II$_{\text{Phase I}}$

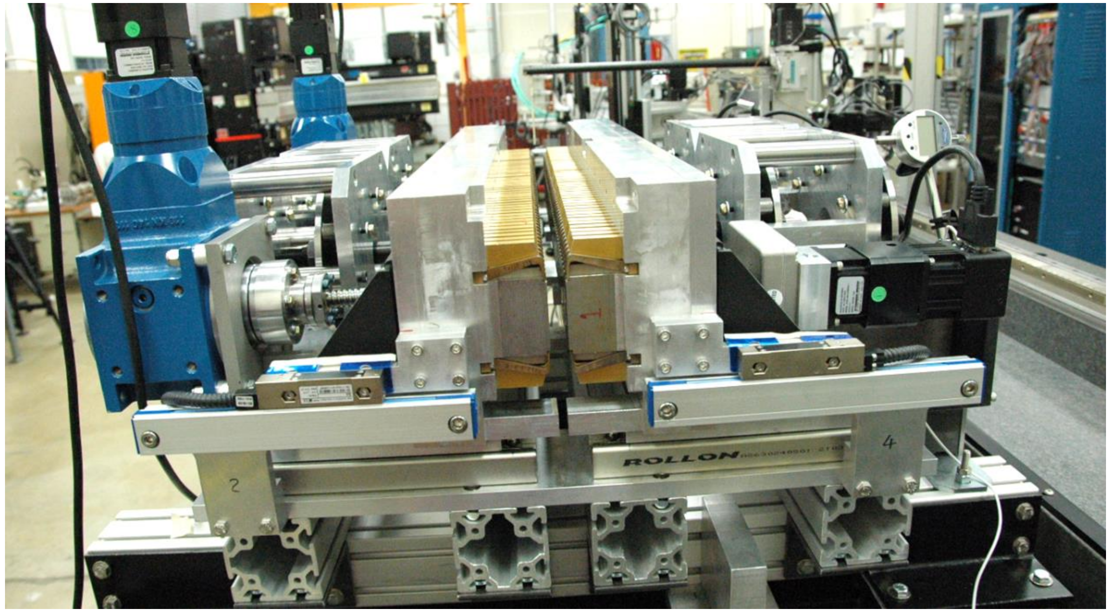


M. Leitner, S. Marks

# LCLS-II Undulator R&D

Two concurrent undulator R&D programs being pursued:

- Superconducting undulator (SCU) - combined Argonne/Berkeley effort
- Horizontal gap – vertically polarizing undulator (VPU) at Argonne




Argonne 0.8-meter VPU test segment

Plan to have a 3 meter prototype in fall 2014

E. Gluskin, S. Prestemon, et al

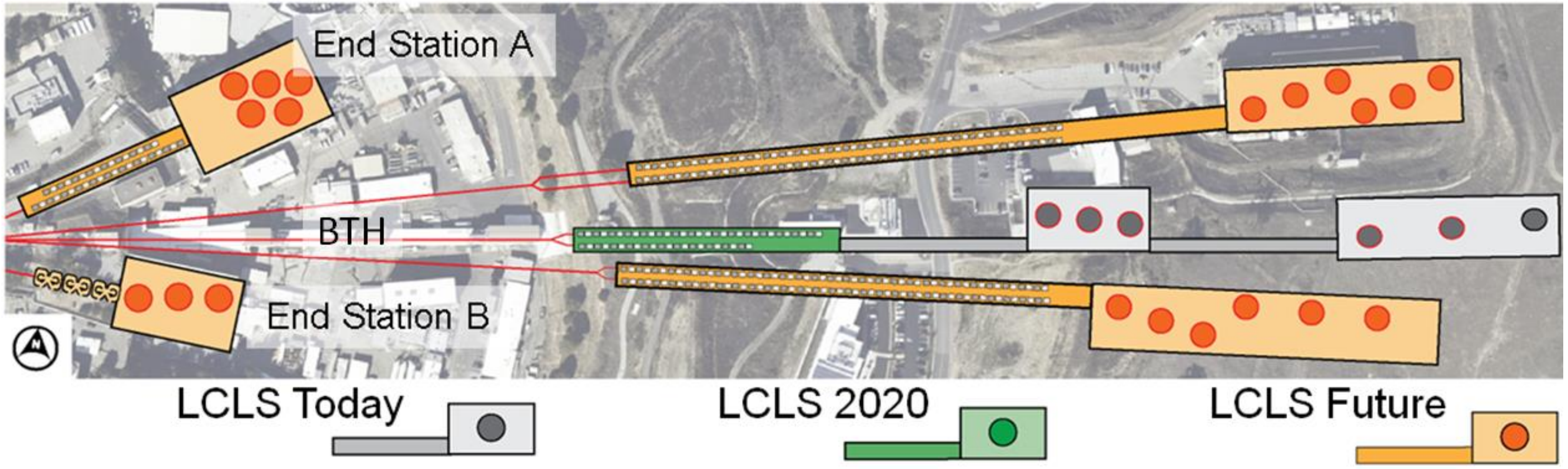
# HGVP undulator prototype

Full scale prototype with compensated beam displacement

# Future Outlook - Facility Expansion Options

SLAC has extensive infrastructure that will allow expansion

- New tunnels are possible north and south of existing LCLS tunnel (complete design for LCLS-II$_{\text{Phase I}}$) and could be optimized for long, high pulse energy, hard X-ray FEL's
- Original research halls: ESA and ESB suitable for shorter, soft X-ray FEL's should they be developed



# Acknowledgements

**The entire LCLS-II project team:** J. Galayda, T. Raubenheimer, H.D. Nuhn, T. Peterson, D. Cocco

Fermilab

Jefferson Lab
EXPLORING THE NATURE OF MATTER

BERKELEY LAB

Argonne
NATIONAL LABORATORY

CORNELL UNIVERSITY
FOUNDED A.D. 1865